PRE-STRESSED STEEL CABLES AND BARS IN CONSOLIDATION OF MONUMENTAL BUILDINGS

L0RENZO JURINA
Politecnico di Milano – Dept. of Structural Engineering
Piazza L.da Vinci 32, 20133 Milano, Italy

ABSTRACT

Steel, and stainless steel in particular, is taking on an increasing important role in the conservation of buildings of historical value. This is due to a series of obvious advantages: reduced bulk, limited cost, excellent strength, the possibility of immediate recognition and reversal of restoration work, and, lastly, durability comparable with the structure in which it is used. Ever since many centuries, chains, cramps, and connecting elements made of metal have been used to absorb traction stress produced by the horizontal component of forces in arches and domes or to improve faulty connections or replace missing ones. At present days reinforcing "passive" steel elements and "active" pre-stressing steel elements, in form of cables or bars, are more and more adopted and accepted.
The paper shortly illustrates some examples in which steel cables have solved, efficiently and in some cases gracefully, difficult static problems involving damaged masonry structures.
A tall medieval tower in Pavia, two castles of XV century in northern Italy, a pair of twin minarets in Azerbaijan and some damaged masonry vaults have been recently studied and fully restored. Technological, structural and execution aspects will be illustrated in relation to these examples in which a *criterion of minimal intervention* was chosen.

INTRODUCTORY REMARKS

Today there is no unanimous reply to the question "how a restoration has to be carried out?" It is therefore necessary to define what one means by the term "restoration" and the principles by which one operates in this field.
The international documents – the various "restoration charters" – offer a useful though not exhaustive point of reference. The principles they set out demand reasoned adoption rather than a scholastic act of faith. Above all they demand that decisions be taken in the light of the ***specific situation*** of the monument to be restored.
There is one element that may be considered common to all restoration projects: in-depth analysis of the constituent materials and the structural condition of the monument in question.

In our opinion, the crucial value of reference is that ***the safeguarding of the memory*** constitutes the best foundation for the future. The monumental complex indeed offers unrepeatable testimonies to the culture of the people who produced it and who have looked after them ever since; the loss or alteration of a part is always irreversible and would seriously impair the cultural growth of a civilization. It follows that the conservation of these monuments must be planned and executed on the basis of a thorough analysis of the buildings, using materials and techniques that are ***compatible*** with those they embody already and so that they remain an expression of the place they occupy and of the continuity of their own history. The restoration must therefore strive to ensure the permanence of the monument with all the marks and layers of time and history that characterize its current state.

With regard to any consolidation work of an historical construction it must be stated that it is part of a wider-ranging process that we may call "the practice of conservation".

The *first principle* to state is that we must accept the historical building in its current state (the building is the primary source of knowledge) as a significant testimony in its full complexity, and that we must maximise our total knowledge of the building, assigning equal value and importance to all components of the building and to all the materials contained in it. The work to be performed will, therefore, be determined through careful and specific observation. In other words, it is important to study the individual object as a unique, unrepeatable instance.

The *second principle* is that strengthening, considered as a single, exceptional intervention or as a part of a larger project for work on a building, must be organised with a cognitive, scientific approach to phenomena of degradation and ruin to assess **if and when** there is an effective need for intervention.

An object is irreplaceable in that it is **unique**, because of elements of its material culture, because of its historic nature, because of the relationship that links it to other events, because it can be studied through many distinct types of reading. The type of work and the technology that best achieve the aims listed above are then selected on the basis of these assessments.

Ever since the Middle Ages, and even before, chains, reinforcement rings, cramps and connecting elements made of metal have been used to absorb traction stresses produced in the masonry by the horizontal component of forces in arches and domes or to improve faulty connections or replace missing ones. Important examples can be found in a number of monuments of the past, for example the metal components in Brunelleschi's dome for Santa Maria del Fiore in Florence, or works involving use of chains in thrusting arches and vaults or encircling of cracked columns.

Metal components frequently appear in historical buildings, either in restoration work or in the original construction. Not only is steel, generally speaking, compatible with the historical building in terms of both **resistance** and **rigidity**, but also in the case of stainless steel, any fear regarding lack of **durability** is really unfounded.

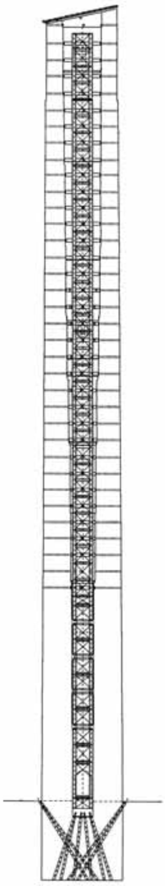
Steel, especially stainless steel, can be used in work which will stand alongside the existing construction and permit it to be read. Nothing is replaced or removed, and a recognisable addition is made which can easily be removed and is therefore reversible. It is up to the designer to come up with a solution which is aesthetically satisfactory and harmonised with the whole. Steel is naturally predisposed to this compositional use of additions, providing considerable strength with minimum bulk.

The projects described below are to be considered not only as examples of the use of steel, and more particularly stainless steel, in strengthening of historical buildings, but also as specific engineering choices which have tried to identify the best possible solution for the specific case in point in each project.

EXAMPLES OF APPLICATION

San Dalmazio Tower, Pavia (Italy)

This 45 meters high, XI century, brick tower showed many local damages and lacks in the masonry and long vertical cracks along the four walls. The strengthening project involved construction of a new inner metal tower made partly of carbon steel and partly of stainless steel, which is fully exposed and completely renewable but entirely located inside the tower so that it could not be noticed from outside but for of a number of discrete signals declaring its presence; in other words, a **“tower within a tower**”. The dead load of the masonry is partially transferred to the inner tower by means of about 300 prestressed **sub-vertical cables,** laying in the interstice between the masonry and the steel tower**.** The new structure takes into account the culture of preservation, such as adoption of strengthening work which stands alongside the existing structure (it could be called a “crutch” if the term did not have such negative connotations), the reversibility of the work, and its easy recognition as belonging to a different historic period. The new construction collaborates structurally with the masonry tower. Not only does the new tower provide static assistance by removing part of the vertical load, increasing resistance to horizontal loads and improving ductility, but it helps make maintenance easier for itself and for the old masonry tower. In fact there is space inside the new metal tower for a rack elevator permitting easy access to the inside of the tower, allowing inspection and ongoing planned maintenance.

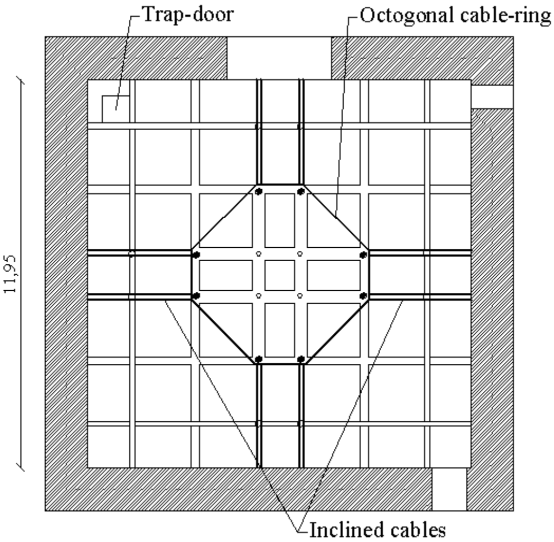


Accessibility is an important factor in maintenance, for by encouraging use of all parts of a structure we promote work required for their use, at least in relation to frames, roofs, and finishes, which are where structural decay often starts. In the strengthening project on the masonry tower, additional stainless components were used to create **radial tie bars** that pass through regularly spaced horizontal holes just existing in the masonry. The aim is to “*confine”* laterally the walls adding horizontal loads, thus connecting the various vertical layers of the masonry. As seen, the more expensive stainless steel material is used in the areas which are most exposed to the air and most closely in contact with the old masonry.

Visconteo Caste, Pavia (Italy)

The Visconti's XV century castle in Pavia has suffered the vicissitudes of time and now has only three remaining sides and two corner towers, which have been subjected to repeated restoration and modification. In the early XX century the Southwest Tower was in very poor conditions, with fissures and depressions in the large vault on the first floor, so that in 1925 the flooring and the filling material was completely removed. A new reinforced concrete floor was constructed above the vault, rigidified with rib beams, to provide support for live loads. For greater prudence (as it seemed at the time) the masonry vault was *suspended* from the reinforced concrete floor using twenty metal rods, 30 mm in diameter. In 1995 the concrete floor, which had been left exposed for many years, was paved. Only a few months later the pavement unexpectedly lifted and cracked visibly. The diagnosis was *viscous yielding* of the reinforced concrete floor subject to a considerable permanent load. The floor lowered and required the pavement itself to take on a structural role, subjecting it to compressive stress that leaded to a buckling phenomenon. This theory was confirmed by inspection of the hollow between the vault and the floor, which revealed that some of the 20 metal "safety" tie bars had buckled due to compressive stress, so that a part of the reinforced concrete floor was resting on the vault below it. The first action taken was a modification of the connection that permitted them to act as tie bars only, not as struts. The concrete in which they were embedded at the top was in fact removed to leave them free to slide vertically only in one direction.

The problem that remained was construction of a new structure alongside the existing floor to minimise any further yielding, taking into account the fact that only 27 cm existed between

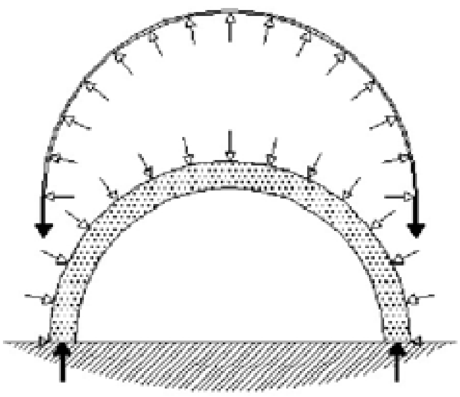


the vault and the floor at the crown, which did not permit new structures of sufficient structural height to be introduced. As is often the case, the solution lay in finding a "way around" the difficulty. An "*octagonal ring*" about 500 cm in diameter was created out of stainless steel bars and a set-up of bars and struts all within the space between the extrados of the vault and the horizontal floor. The ring, positioned concentric to the vault but 60 cm below the height of the crown, became the point at which eight pairs of diagonal tie rods coming from the upper edges of the lattice converged. The ring therefore serves to ensure the structural continuity of the tie bars, going around the top of the vault while permitting the correct structural height to be achieved. The cables are subjected to uniform traction controlled by adjusting the eight stainless steel struts. A large screw at the end can be used to lengthen and buck the struts, constrained by the reinforced concrete floor above.

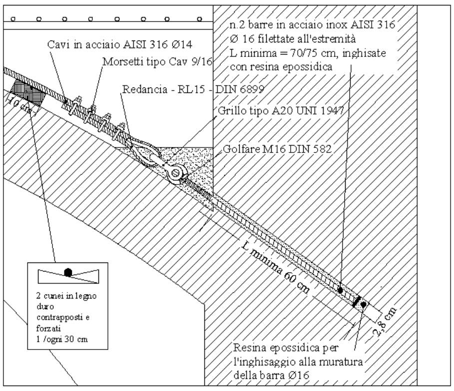
Steel provided the designer with the resources required to construct a lightweight structure adaptable to the requirements of the circumstances. In particular, stainless steel was used for the entire structure in order to ensure durability, which must always be given in due consideration even when, as in the case in point, measures were taken (a small trap-door in the wooden floor) to make the structure accessible and visible to permit maintenance.

The vaults of the Medici Castle in Melegnano (Italy)

It was necessary to restore an adequate safety margin for the vault of certain rooms in the XV century Medici Castle in Melegnano, near Milan, Italy, to permit public access.
Inspection of hidden parts has indicated that replacement of the wooden chains in the extrados with a smaller number of metal chains positioned at the elevation of the pavilion vault has not entirely restored the load-bearing capacity of the vault and therefore its safety.
This is partly due to the presence of wooden chains which intersect the vault, interrupting its continuity and thereby decreasing its resistance; they were left in place even when they no longer had a structural function, thus creating a sort of ***"continuous weak joint"*** between various adjacent portions of the vault which, because of that, no longer work monolithically.
The various portions of the vault thus work disjointed, essentially leaving the various portions to support the loads on them independently. This circumstance takes on a greater importance in the "pavilion-shape" vaults that behave almost like two perpendiculars arches spanning the distance between the walls. The intervention involves restoration of the monolithic nature of the vault by demolition of the wooden chain in stages (working on small sections at a time) and replacing it with new masonry scarfed with the existing masonry.
After some experimental tests, a special technique was suggested by the author to increase the load-bearing capacity and safety of the vaults, in which a series of stainless steel cables parallel to the extrados are used, in a technique referred to as the "reinforced arch method".



These cables are connected to the masonry to the side by means of a system of threaded bars, thimbles, fasteners, and eyebolts, all made of stainless steel, and put under traction by a system of screw couplings. The vault is thus subjected to radial loads which increase its compression, improving its resistance to pressure-flexure induced by incidental loads, especially asymmetrical loads. The technique achieves a result equivalent to or in some cases better than that obtainable with the traditional covering of the vault from above with a layer of collaborative reinforced concrete. In this way the additional structure does not interfere with the material and structural reality of the existing building and is invasive only to a limited extent. Stainless steel's versatility, strength and durability make this a lightweight, reversible,

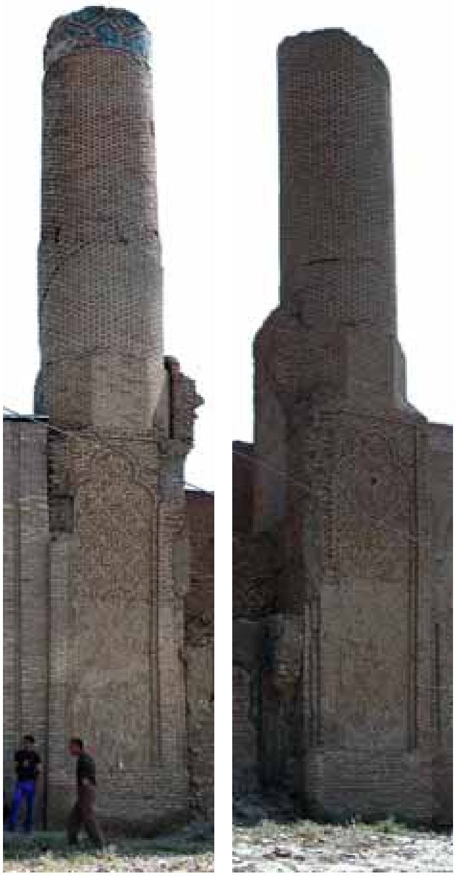


non-invasive solution that can easily be maintained and kept under control over time (by progressively tightening the tie bars).

The twin minarets in Karabaglar village (Azerbaijan)

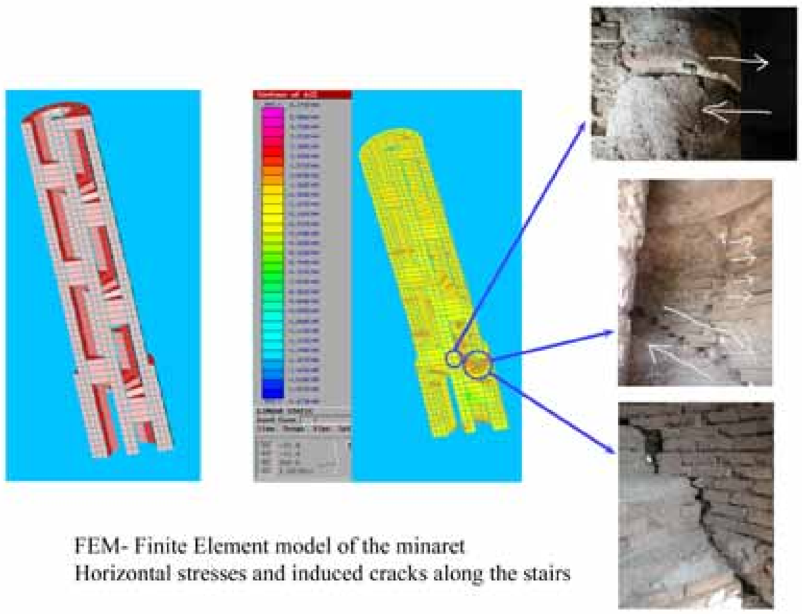
The Nakhichevan –city famous monumental complex in south Azerbaijan almost certainly inspired that of the near village of Karabaglar, which comprises a monumental gateway flanked by twin minarets (both now truncated) and a mausoleum. The existence of constructions between the monumental gateway and the mausoleum of Ghudi Khatun suggests that they are one of the oldest examples of the genre in the entire area of ancient Iranian culture. The brick structure of the twin minarets at Karabaglar appears to be of the simplest and most widely used types in ancient Iran, with an ***internal spiral staircase*** revolving around a central spindle. A parallelepiped structure in brick rises from stone foundations, and the entire exterior is sheathed in brick. The minarets are currently of different heights and bear many signs of cracks. There appears little doubt that the structural damage has been caused by one or more seismic events; first the minarets were probably “decapitated” as a result of the whiplash effect of an earthquake shock; later shocks probably caused the motion of translation and rotation of the minaret at its base.

Correct interpretation of the phenomenon will require research to identify the type and characteristics of earthquakes that have struck the area in the past. An initial interpretation however has been done, using a discrete element numerical model of the structure in a non-fissured state. It will follow another analysis in its current state with cracks.



As for **the taller minaret,** the first task was to investigate the kinematical action underway in an attempt to provide a quantitative description of the phenomenon of expulsion of part of the masonry in the lower half of the minaret. It is clear that earthquake stress was severe in the circular-section lower part. The additional presence of two factors – a big window that interrupts the continuity of the walls and a spiral staircase that gave raise to a substantial structural eccentricity – caused a sideways slippage of the minaret, which at the same time rotated in a clockwise direction. The photographs clearly show the spiral dislocation of the bricks, visible both inside and outside, immediately above and below the section held in place by the bricks of the staircase. In other words, ***the spiral staircase very probably acted simultaneously as a local reinforcement agent and as an element of global asymmetry***; the combined effect was cracking due to rotation-translation motion. The zones of masonry immediately above and below the spiral staircase show signs of severe concentrations of tension that could have caused the masonry to break.

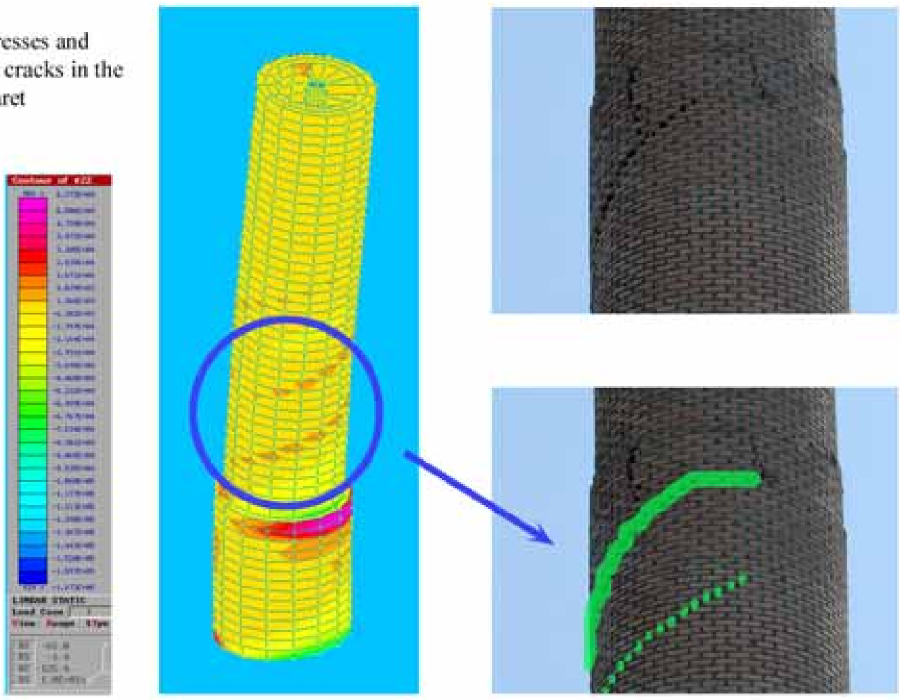
As for **the lower minaret,** it was also, probably, “decapitated” by a seismic event; in this case, however, the absence of discontinuity in the walls (by contrast with the window and the door in its twin) avoided the dramatic consequences visible in the taller minaret. In fact it seems to feature just one horizontal lesion, due to shearing stress.



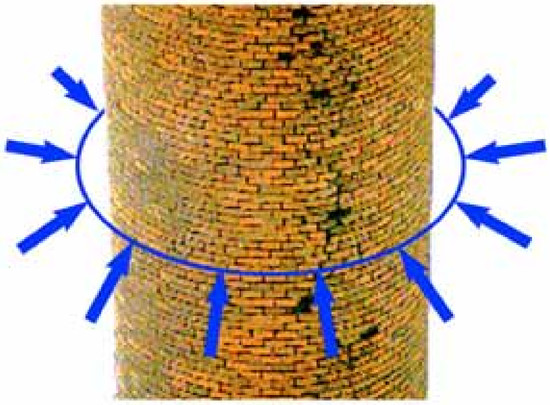
FEM- Finite Element model of the minaret
Horizontal stresses and induced cracks along the stairs

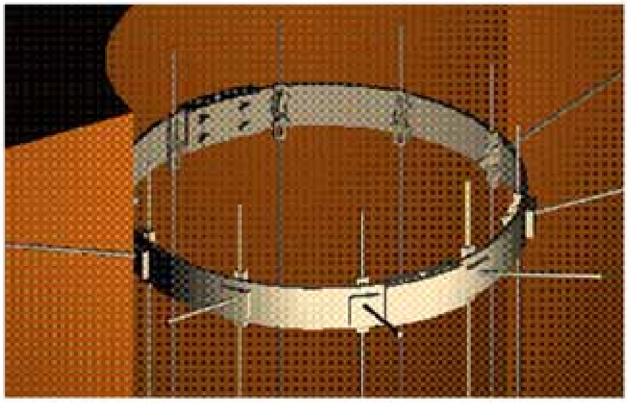
Numerical analyses have highlighted, also here, a marked torsion affecting this minaret.
On the basis of the data currently available, we have noted a fairly good correspondence between the pattern of cracks visible on the monument and the areas subject to the greatest stress according to the numerical analyses.
To reach objective and demonstrable results, however, the model will have to be “*cross-checked*” against free oscillation tests conducted on site and using artificial noise or natural events such as wind, with measurements being taken by accelerometers distributed over the surface of the structure in question. Similar experimental and numerical investigations, aimed

Traction stresses and consequent cracks in the tallest minaret



to parameter identification, have been conducted by the author on various masonry towers in Northern Italy.
The chosen system of consolidation must support the existing structure, must be located inside the minarets and must involve only modest intrusion into the existing masonry. It has to offer immediate and substantial improvement to the resistance and ductility of the structure; it should not, however, substantially alter its rigidity in order not to comprise its interaction with the adjacent structures. The consolidation system has to be of the “active” type, i.e. capable of





acting immediately, even before the seismic event, by adopting a system of pre-compression.
It is under investigation the feasibility, for example, of laying rings of thin (6 mm diameter) stainless steel cable along the mortar joins in the external wall in the areas of major lesion.
A complementary method that is under consideration is the use of *radial binding elements*. The method is suggested by the current presence in the minaret of strips of wood placed along the edge of every step but now often missing or rotted by rainwater. These wooden elements were certainly intended to prevent damage to the edge of the steps but it is also possible that they had a structural function by using a traction-resistant material to bind the external wall to the central spindle. It might be beneficial to conceive of consolidation as a revival of this system of radial retaining, introducing new edging strips of wood, below which would be inserted a length of small-diameter stainless steel cable, injection-anchored to the masonry and capable of performing a retaining function. Vertical cables, parallel to the inner surface of the cylindrical wall, will be added too, to contrast the structural eccentricity induced by the global out of verticality of the minaret. More details can be found on **www.jurina.it.**

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